Chapter 73

EFFECTS OF STRATIFICATION ON CARBON MONOXIDE LEVELS FROM MINE FIRES

Ronald S. Conti and Charles D. Litton

U.S. Department of the Interior, Bureau of Mines
Pittsburgh Research Center, P.O. Box 18070
Pittsburgh, PA 15236

ABSTRACT

This report describes the results of research conducted in the Bureau of Mines Experimental Mine at Lake Lynn Laboratory to determine the effects of air velocity, sensor spacing, and stratification of CO levels on the detection of slowly-developing coal/conveyor belt fires. In general, the time to detect a developing fire is calculated assuming an average CO level that has mixed completely with the ventilated airflow. The data indicate that CO sensors placed near the roof of an entry take advantage of buoyant-induced stratification of combustion products, resulting in earlier detection of developing fires. Even during the low-temperature, smoldering stage of a fire, the combustion products will tend to stratify near the roof, and once flaming occurs, the degree of stratification increases markedly. As one would expect, at higher air velocities, the degree of stratification is less than at lower air velocities, although still significant, especially during the flaming stages of the fire.

INTRODUCTION

Fires present a significant hazard to personnel in underground coal mines. If not detected early (Conti and Litton, 1992), fires can produce toxic combustion products (Hertzberg, et. al., 1977) and smoke, which can travel quite rapidly through a mine with the ventilation airflow and contaminate areas downstream from the fire. Most fires start from a relatively small ignition source and if undetected may increase in intensity to sizes sufficient to propagate beyond the ignition source, and then spread swiftly along mine entries. The now larger fires can contaminate entire areas downstream and disrupt ventilation airflow. These extreme situations can be avoided when fires are detected in the early stages of development, leaving sufficient time to safely evacuate mine personnel, and locate and extinguish the fires.

During the incipient or smoldering stages of a fire certain gases are produced, most notably, carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O). Of these gases, carbon monoxide is most easily detected at very low concentrations (0-15 ppm) with sensors that are relatively inexpensive. Carbon dioxide and water vapor sensors are impractical because these sensors are generally more expensive, background levels of CO_2 and H_2O must be subtracted from the total readings, and smoldering fires produce low concentrations of CO_2 and H_2O, but generally produce detectable levels of CO.

The successful detection of a developing fire in a mine using CO sensors requires a fire large enough or extensive enough to generate bulk average CO levels greater than or equal to, the alarm threshold level of the sensor. Bulk average levels are obtained when the fire-produced CO completely mixes with the ventilated airflow. The CO is then transported to the sensors by ventilation; the transport time is equal to the sensor distance divided by the air velocity. At low air velocities this time can be long, resulting in a significant delay in the time to alarm. Increasing the airflow decreases the travel time, but also dilutes the CO levels which increases the sensor response time. Sensor response time is also an important detection event. Although, in general, most sensors respond rapidly, the use of a sensor with a long response time can increase the time to alarm.

From 1970 to 1990, 307 underground coal mine fires (Luzik, 1991) were reported by the Mine Safety and Health Administration (MSHA). Two of the most recent fires are of particular interest. A fire at the Pattiki Mine, Southern Illinois, in November 1991,

which resulted in a portion of the mine being sealed because of frustrated firefighting efforts due to the fire magnitude and delay in initiating activities to fight the fire. At the Mathies Mine, Finleyville, PA, in October 1990, a fire resulted in the mine being sealed, several injuries sustained, and a loss of over 400 jobs. Firefighting efforts may have been improved in both of these fires, if firefighters were able to respond in the incipient stages of the fires. This could only be accomplished with early detection.

This paper presents data on the early detection of coal conveyor belt fires and the amount of time saved or lost with respect to sensor location and ventilation airflows.

EXPERIMENTAL PROCEDURE

The studies on the effects of stratification on CO levels were observed in experiments conducted in A-drift of the Bureau's Lake Lynn Laboratory, formerly a limestone mine (Mattes, et. al., 1983). This multipurpose mining research facility is primarily used to conduct fire and explosion prevention research. The average entry dimensions of the underground mine are 2.1 m wide and 5.8 m high (average cross-sectional area of 12 m^2). A detailed layout of a typical underground fire and detection scenario is shown in the perspective view in Figure 1. During the experiments, the airflow of the mine is reversed so that the combustion products are exhausted through the main fan. The airflows can be adjusted via one of the four positions of the main fan, adjusting the moveable bulkhead doors in D-drift and E-drift (not shown), and erecting temporary stoppings at the last cross-cuts of B- and C-drifts. The air-flow is monitored with a vane-anemometer 15.2 m inby the fire zone.
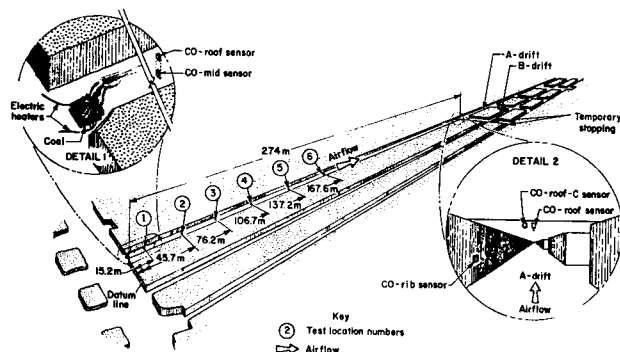

Figure 1. PERSPECTIVE VIEW OF UNDERGROUND FIRE TEST, DEPICTING CO SENSOR LOCATION FOR SIX TESTS

Products of combustion detectors were used at two positions along the mine entry. Two diffusion-type electrochemical CO sensors (see Figure 1, detail 1) were mounted at a predetermined distance inby the fire zone in the middle of the entry. The range of sensor spacing was between 15.2 and 167.6 m and were positioned at 30.5 m increments for each test as indicated by the circled test numbers. One CO sensor was mounted near the roof and was labeled CO-Roof and would indicate the location of that sensor during one of the six test positions. The other CO sensor was mounted directly below, 0.65 m from the floor and was labeled CO-Mid.

Three diffusion-type electrochemical CO sensors were mounted as shown in detail 2 of Figure 1, in the entry cross-section at a point 274 meters inby the fire zone. The two that were mounted at the roof, were labeled CO-Roof and CO-Roof-C and represent two different brands of CO sensors. The third CO sensor was mounted 0.66 m from the floor on the rib, identified as CO-Rib and was of the same brand as the CO-Roof sensor.

The test scenario studied was a slow-developing coal/conveyor belt fire. Seven electric strip heaters with a combined power rating of 9.5 kW, were embedded into a 1.2 by 1.2 m coal pile and used to ignite 75 kgs of coal. Six 10.2 by 22.8 cm strips of rubber conveyor belting were evenly distributed in the coal pile which was then seeded with approximately 0.75 kgs of Pittsburgh pulverized coal dust. Full electrical power was applied to the heating elements. Visible smoke from the coal pile was usually observed in 2-3 minutes, with flames emitting from the coal approximately 9 minutes later.

TEST RESULTS

Figure 2 depicts the bulk average CO levels 274 m from the fire as a function of time at two airflows. The CO levels shown are average values from six tests, conducted at each airflow. Time "0" corresponds to the instant of flaming ignition of the coal pile and not to the time when power was supplied to the electrical heaters. The negative time corresponds to the smoldering stage and the positive time to the flaming stage. The transport time of the CO produced from the fire to the 274 m location was computed by dividing the distance of the sensor from the fire by the air velocity. For example, the computed transport time at the lower airflow was a rather long 10.4 min. Increasing the airflow to 1.02 m/s decreased the travel time to 4.5 min. The low CO levels of 1 to 4 ppm were detected much sooner at the higher velocity than at the low velocity. For instance, the time required for the sensors

located 274 m from the fire to detect the initial CO concentration of 1 ppm from the smoldering coal pile at the lower airflow was 3.4 min after flaming ignition or 15.2 min in real time. This was over 5.4 min longer than at the higher air velocity, simply due to the longer travel time of the combustion products at the lower velocity. At 8 or 9 ppm, the CO was detected earlier at the lower airflow by 2 to 3 minutes, primarily due to lower dilution by the ventilation airflow, which tended to compensate for the longer travel time.
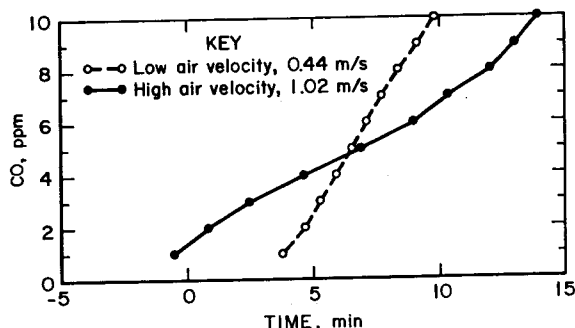

Figure 2. BULK AVERAGE CO LEVELS AT 274 METERS VERSUS TIME, AFTER FLAMING IGNITION. THE AVERAGE TIME OF FLAMING AT THE LOW (0.44 M/S) AND HIGH (1.02 M/S) AIR VELOCITIES, WERE 11.78 AND 10.37 MINUTES, RESPECTIVELY

A comparison of the low and high air velocity CO production rates versus the time prior to and after flaming ignition is shown in Figure 3. The data in the negative time zone reflect the CO production rates during the smoldering stages. Flaming CO production rates are shown in the positive half of the graph. It is worth noting that at the low air velocity all of the CO up to 10 ppm was produced during smoldering. At the high air velocity only 4 ppm was generated during smoldering and it required a flaming fire to generate sufficient CO to
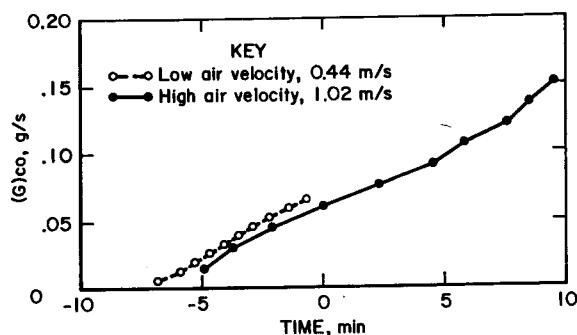

Figure 3. CO PRODUCTION RATES VERSUS TIME DURING SMOLDERING AND FLAMING STAGES OF A COAL CONVEYOR BELT FIRE

reach the 10 ppm level. Although all of the CO up to 10 ppm at the low air velocity was produced during the smoldering stages, none was detected at the 274 m location until after flaming ignition, a dramatic illustration of the influence of long travel times.

Figure 4A and B show examples of CO stratification for the CO-Roof to CO-Mid ratio at two sensor locations for low and high air velocities. Time "0" corresponds to the time at which power was supplied to the electrical heaters. At 45.7 m from the fire at the low airflow (Figure 4A), the CO was somewhat stratified during smoldering, averaging 5 as compared to an average CO ratio of 2.5 at 137.2 m (Figure 4B). This indicates the mixing of the combustion products as they moved downstream away from the fire. During the flaming stage, the CO was more stratified with CO ratios displaying an average value of 28 at 45.7 m and becoming less stratified as the products reached the 137.2 m sensor location. At the higher air velocity, stratification was much less distinct for the sensors immediately downstream, averaging 1 to 2 during smoldering, then increasing to 5 or 6 during flaming ignition. Again, stratification decreased dramatically at the 137.2 m location, with average CO ratios of 1 to 2.
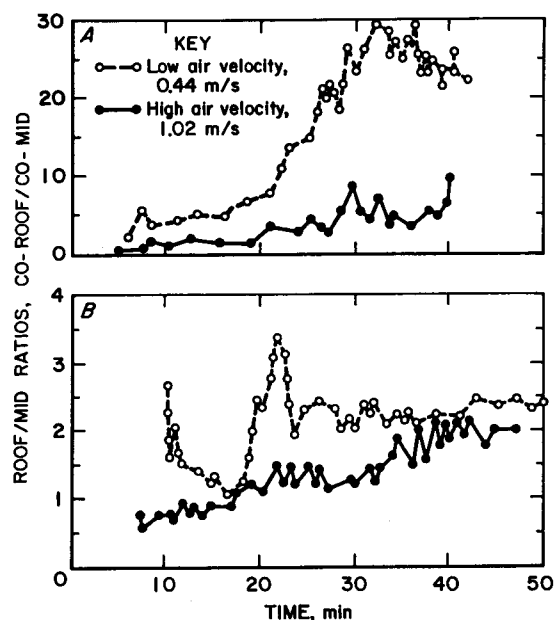

Figure 4. EXAMPLES OF CO STRATIFICATION AT TWO AIR VELOCITIES, (A) 45.7 M SENSOR LOCATION, (B) 137.2 M SENSOR LOCATION

The average stratification during the smoldering stage of the fire at a low and high airflow are shown in Figure 5A. As can be seen, the CO ratio was more stratified at the lower air velocity compared to the high

air velocity. The readings at the sensors located 45.7 m downstream at the low airflow demonstrated a 4-fold increase in the stratification over those sensors at the high airflow. The degree of stratification decreased dramatically at the lower air velocity as the sensors were placed further downstream. For example, at 76.2 m the CO-Roof to CO-Mid ratio was 3.5 compared to less than 2 at 167.6 m. The average stratification during the flaming stage is presented in Figure 5B. As can be seen, the level of stratification is greater at both high and low air velocities for the flaming stage compared to the smoldering stage (5A). This is to be expected for the flaming stage since the buoyant forces are much greater due to the higher gas temperatures produced from flaming combustion. The degree of stratification decreased rapidly for both airflows as the products moved further away down the entry from the fire.
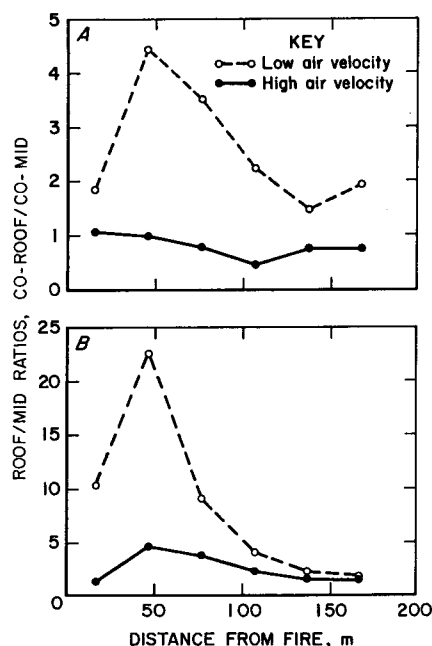

Figure 5. AVERAGE CO STRATIFICATION AT TWO AIR VELOCITIES, (A) SMOLDERING STAGE (B) DURING FLAMING STAGE

IMPACT OF STRATIFICATION

The preceding discussion has clearly shown the levels of CO stratification that evolve from both smoldering and flaming fires. Clearly, in order to take advantage of this stratification, one should locate sensors near the roof of the entry. It is not readily apparent as to the lengths of time that can be saved through earlier alarms by doing this. Figures 6 and 7 show the actual time that was saved by locating the sensors either near the roof or near the center of the entry at distances of 45.7 and 137.2 m, respectively.

In general, times to detection are calculated on the basis of bulk average CO level and a transport time equal to the distance of the sensor divided by air velocity. For these data, the bulk average CO levels are those measured at the 274 m location. By subtracting the travel time from the measured arrival time of CO at 274 m, the arrival time at any of the other sensor distances of the bulk average CO may be calculated. This time is then compared to the actual measured arrival time of the roof CO or mid CO at any other test location. The time saved (or lost) is the difference in arrival time of a given measured level of CO at a sensor and the calculated arrival time of the bulk average CO at the same ppm level.

At 45.7 m (Figure 6A), about 1 to 3 minutes were saved by locating sensors near the roof at the lower velocity. This may not seem significant, but it should be remembered that these levels of CO were produced during smoldering and the buoyant forces were considerably weaker than during the flaming stage. It should be noted that for the mid-entry CO sensors (Figure 6B) at the lower air velocity, CO levels of 5 ppm and above were never reached at this distance. This would mean then, that the CO, having missed the first sensor, would have to travel another sensor spacing before it could be detected by the next downstream mid-entry sensor, thus adding additional time to the detection process.
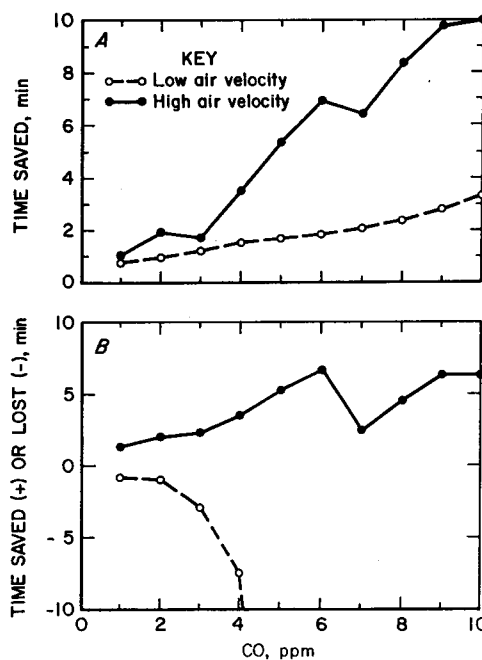

Figure 6. TIME SAVED AT THE 45.7 M SENSOR LOCATION DURING TWO AIR VELOCITIES, (A) ROOF CO SENSOR, (B) TIME SAVED OR LOST FOR THE MID CO SENSOR

At the higher air velocity, as much as 9 to 10 minutes were saved by locating sensors near the roof. Although time was also saved by mid-entry sensors, there was more time saved by the roof sensors.

At the 137.2 m distance as depicted in Figure 7, the time saved was less because mixing had occurred. It should also be noted that for the mid-entry sensors (Figure 7B), even at the higher air velocity, time was lost for CO alarm levels greater than 5 ppm.
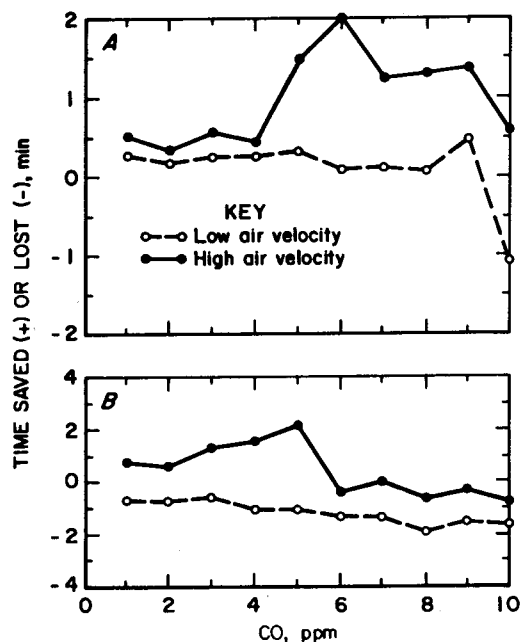
Figure 7. TIME SAVED AT THE 137.2 M SENSOR LOCATION DURING TWO AIR VELOCITIES, (A) ROOF CO SENSOR, (B) TIME SAVED OR LOST FOR THE MID CO SENSOR

Figure 8 shows the average time saved or lost for both roof (Figure 8A) and mid-entry (Figure 8B) CO sensors at the low and high air velocities. At the low air velocity roof sensors save an average of 1.4 minutes while mid-entry CO sensors lose about 2.5 minutes. At the high air velocity, roof sensors save 2.4 minutes and mid-entry CO sensors save about 3.1 minutes. It is important to note that roof CO sensors will usually save time, while mid-entry CO sensors often lose time, resulting in detection delays. As a result, locating sensors near the roof takes advantage of any stratification that may occur, with the net effect being more rapid detection of developing fires.
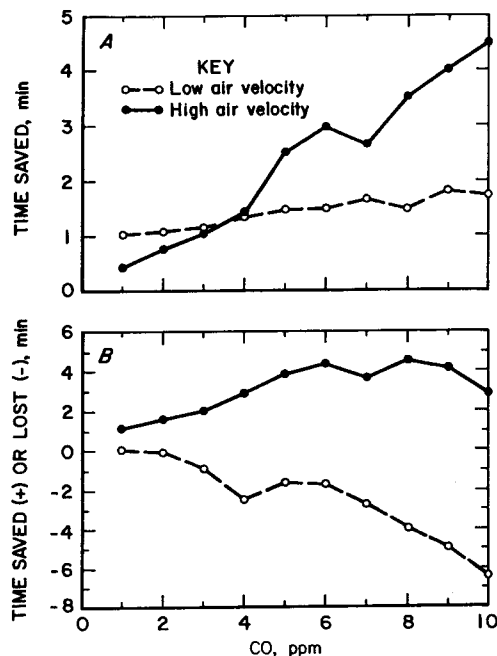
Figure 8. SUMMARY OF AVERAGE TIME SAVED OR LOST WITH RESPECT TO CO ALARM LEVELS, AT SIX SENSOR LOCATIONS, (A) ROOF CO SENSORS, (B) MID CO SENSORS

CONCLUSIONS

These experiments clearly show the effects of air velocity, sensor spacing, and CO stratification on the detection of small coal/conveyor belt fires. For low air velocities, the travel time of the combustion products represents the most significant interval in the total detection time. Locating sensors near the roof at the lower air velocity can reduce the impact of long travel times between sensors. Also, at low air velocities, CO sensors should never be located near the middle of the entry because such a location actually results in longer time delays.

At the higher air velocities, the detection of CO is limited more by the production of CO and subsequent greater dilution than at lower airflows. Again, locating sensors near the roof can reduce the impact of this effect. Earlier detection can be achieved by locating sensors near the roof, thus increasing the time available for personnel to respond to the fire and initiate appropriate action. The most important element here is time, and the amount of time saved because of early detection can increase the probability of safely evacuating mine personnel and enhance the firefighter's ability in control and extinguishment of fires.

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